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Original communication

A comparative study of topological and sex differences in fingerprint ridge density in Argentinian and Spanish population samples

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ABSTRACT

Although several studies have recently assessed sex differences in fingerprint ridge density and its variability in human populations from different origins, such a study has not been carried out yet in the Amerindian population. The goal of this study was to determine the topological and sexual differences in fingerprint ridge density (RD) in native subjects from two samples of northwestern Argentina (Jujuy province) living at different altitudes. The results were compared with those obtained from a Spanish population sample. The study was based on data from all 10 fingerprints of 393 adult Argentinian men and women, 193 from the Puna-Quebrada region (more than 2500 m above sea level) and 200 from Ramal (500 m above sea level). Ridge density was assessed for three different areas (radial, ulnar and proximal) for all 10 fingers of each subject. In both samples, significant differences between areas were obtained, so radial RD > ulnar RD > proximal RD. No significant differences were found between samples in males, while females from both samples significantly differed in the radial and proximal areas. Females have higher RD, so narrower ridges, than men, in all areas and all fingers. Application of Bayes' theorem allowed us to obtain a ridge density threshold for discrimination of sexes in Argentinian samples and the threshold for discrimination of populations between Argentinian and Spanish samples. These results can be useful for forensic use.

1. Introduction

The formation of the epidermal ridges is a complex process influenced by numerous genetic and environmental factors that affect the width of the ridges and potentially their density. Dermal papillae ridges are polygenic characteristics that form very early in prenatal development and are considered fully developed by the sixth month of fetal growth.[1–4] The environmental effects are limited to the first few months of embryonic life. Once formed, and in the absence of lesions, these ridges will remain essentially unchanged throughout the life of the individual. Therefore, epidermal ridge number is not affected by age, and as the body in general grows—the hands and feet in particular—the ridges will increase their width but not their number or pattern.[5–8]

The outer morphology of the friction ridge skin is a direct reflection of its function. The ridges allow the hands and feet to grasp surfaces firmly, and the creases allow the skin to flex.[9] In addition, fingerprints likely enhance the perception of texture by increasing vibrations in the skin as fingers rub across a textured surface.[10]

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Studies of fingerprints' variability in human populations have demonstrated the usefulness of the information obtained about these characteristics for understanding the evolution and genetic structure of human populations,[11,12] for characterizing syndromes and diseases,[13–15] and for personal identification in the field of forensic science.[16–19] Regarding this last aspect, although fingerprints have performed a central role in forensic sciences for many decades, not all the dermatoglyphic features have received the same interest by the specialists. For instance, few studies have dealt with features as *minutiae*,[19–23] or epidermal ridge width.[24–32] Fingerprint recognition is one of the most widely used biometric systems, and its use has also extended from personal authentication to governmental and civil applications. Automatic fingerprint recognition systems must be capable of handling fingerprints and palmprints from a diverse range of ages and both sexes. However, neither the impact of sex on such systems nor the possible differences among human populations have received much attention from the research community.[32,33]

Epidermal ridge breadth or thickness presents topological, finger and sex variability as well as differences between populations.[24,25,27–29,31] This variability has been overwhelmingly studied by means of the core-delta ridge count, but this classic count methodology does not allow assessing the complete topological distribution of the ridge density on the fingerprint's surface.[34,35] Moreover, it has the disadvantage of not being able to define a core in the arches that enables its valuation. However, this type of pattern is worth studying, given that its low frequency affects the weight of evidence.[36]

The first method that allowed for the assessment of the ridge density from the full surface of fingers and palmprints and suitable to all types of patterns was developed by Cummins et al.[24] In recent years, some studies have explored the forensic applications of this feature for inferring the sex of an individual from unknown fingerprints found at a crime scene. These studies have been carried out using samples from different populations: Caucasian and African American,[37] Spanish Caucasian,[38] Egyptian,[39] Indian[40–42] and Chinese and Malaysian.[43] Recently, this methodology has also been applied to facilitate discrimination between populations from sub-Saharan and Spanish origin based on the ridge density observed in a fingerprint impression.[44]

Neither of these two aspects—sex and population discrimination—have been studied in the South American population. Therefore, the aim of this study was to analyze topological, sexual and finger variability in epidermal ridge density in two samples drawn from northwestern Argentina (Jujuy province) and to check their potential usefulness in sex determination in forensic application. In addition, this sample was compared with a Spanish population sample,[38] collected and analyzed using the same study methodology, in order to identify criteria for discriminating between the populations.

The above mentioned forensic applications would help to reduce the number of suspects in the investigation process and to focus the research on the more probable sex and population.

2. Materials and methods

2.1. Populations and sample size

The sample was drawn from the Jujuy province, in the northwest of Argentina. This province is characterized by a remarkable east-to-west altitudinal gradient with four recognized ecological units according to the altitude in meters above sea level—Puna (3500 m), Quebrada (2500 m), Valle (1200 m) and Ramal (500 m)—which have been settled by different populations with a common genetic and cultural origin.[45,46]

Fingerprint impressions from all 10 fingers were collected from a sample of 393 adult individuals, of both sexes, in three of the regions mentioned above: Puna and Quebrada (>2500 m) and Ramal (500 m). Of these, 193 (100 males and 93 females) were from the Puna-Quebrada region (PQ) and 200 (100 males and 100 females) from Ramal (RA). The samples were collected at the Police Academy at San Salvador de Jujuy and at various educational institutions in the province, with the informed consent of the individuals studied. Since some of these students worked, subject occupation was taken into account, and those who were employed in manual work were excluded from the study as this could affect the morphological analysis of dermal papillae ridges.

2.2. Fingerprint density determination

Fingerprints were taken using a variation on the adhesive paper and graphite method described by Aase and Lyons.[47] Fingertip papillae ridges were stained homogeneously with graphite powder and then rolled over the sticky side of an appropriately sized label. Next, these labels were stuck to transparent acetate sheets that had been designed so that each sheet had 10 separate areas for depositing each of the 10 fingerprint impressions obtained from a single individual (Fig. 1a–e). The fingers were assigned the numbers 1 through 10, starting from the right thumb, or finger 1 (F1), and ending with the left little finger, or finger 10 (F10). The image of the fingerprint impression thus obtained provides a mirror image of the fingerprint, similar to that achieved using the classical ink and paper technique. A total of 3930 fingerprints were analyzed. The fingerprints were digitalized, finger by finger, on the premises of the Commissary of Scientific Police at Alcalá de Henares (Madrid). Each true color (24-bit) jpg image had a size of 1496 × 2002 pixels, with a resolution of 200 ppi or 79 pixels/cm.

According to the method described by Acree,[37] ridge density (RD) (i.e., number of ridges in a given space) is measured from the count of ridges found diagonally within a 5 mm × 5 mm square (this provides the number of ridges per 7.07 mm) on the fingertip surface of an area located on the radial side of the distal region of each finger. In the present study, we increased the number of ridge count areas related to Acree's method by including two additional areas, one on the ulnar side of the distal region and the other on the proximal region, following the methodology proposed by Gutiérrez-Redomero et al.[38] To locate the three count areas, the fingerprint is divided into four sectors by two perpendicular axes that cross two ridges above the center of the type of pattern (Fig.1f), with the horizontal line positioned parallel to the interphalangeal joint. In the case of arches without a defined nucleus, the axes intersect at the center of the dactylogram on top of the arch (Fig.1f). In order to facilitate counting, the ridge count was carried out using images enlarged to four times their original size, on which an area of 20 mm × 20 mm was defined.

2.3. Statistical analysis

Ridge count for the three areas was obtained for all 10 fingers of each individual, allowing an estimate of the mean for each area (radial, ulnar and proximal) for each subject. For each population (PQ and RA), descriptive statistics of sample data were obtained for each area by finger and sex. The differences between the sexes were analyzed for the three areas, for each finger and globally (mean for all 10 fingers). In every case, Student's *t*-test was used to statistically analyze sex differences. The areas (radial, ulnar, proximal) were compared by finger, for each sample, using the Friedman (differences among the three areas) and Wilcoxon–Mann–Whitney (ulnar versus radial areas) tests for related samples. For each area,

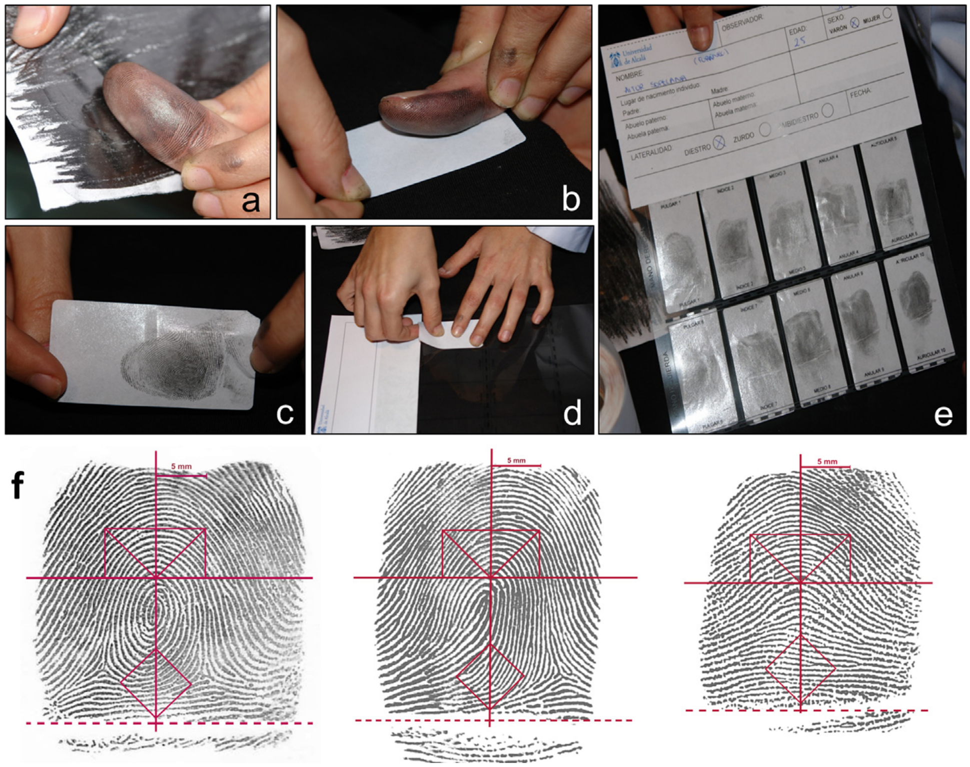

Fig. 1. (a–e)Technique used to collect fingerprint impressions. (f) Location of count areas for different types of patterns (loop, whorl and arch).

the differences between samples (PQ and RA) were statistically analyzed using Student's *t*-test.

The results obtained from this study of Argentinian samples were compared with those of a Spanish population sample, collected and analyzed in a previous study using the same methodology.[38] The topological differences (radial, ulnar and proximal) among population samples (Argentinian-PQ, Argentinian-RA and Spanish) were compared by analysis of variance (ANOVA). Frequencies for different types of patterns were estimated and their relation to RD was analyzed by using one-way ANOVA.

In order to display the RD patterns of each finger by population and sex, a star plot was used,[48] which has been shown to be a valuable tool for identifying patterns and differences among samples. Each star represents a population and sex group to examine the relative values and to locate similar and dissimilar points. As the different star shapes can be clearly observed for each sample, this method of data visualization has considerable potential as a method for the rapid screening, characterization, and comparison of the samples based on multi-elemental data.

Frequencies for different types of patterns and their relationship to RD were calculated. We used the test for independence of characteristics (chi-square) to study the relationship between the type of pattern (arch, radial loop, ulnar loop and whorl) and populations (Spanish and Argentinian). When dependence was detected, we applied a simple correspondence analysis to explain where this dependence was located.

The mean ridge density by area for all 10 fingers was used to obtain the probability of inferring sex and the probability of inferring the donor's population origin by calculating a likelihood ratio (LR).[49]

For sex: let RD be the ridge density, C the male donor and C' the female donor.

LR = probability of observing a given ridge density if the donor was male (C)/probability of observing a given ridge density if the donor was female (C') = $P(\mathrm{RD}|C)/P(\mathrm{RD}|C')$.

For population origin: let RD be the ridge density, C the Spanish donor and C′ the Argentinian donor.

LR = probability of observing a given ridge density if the donor was Spanish (C)/probability of observing a given ridge density if the donor was Argentinian (C′) = P(RD|C)/P(RD|C′).

The value of the calculated LR informs about the strength of support for one of the hypotheses, C or C'. Posterior probabilities were estimated by using Bayes' theorem. Information obtained from both LR values and posterior probabilities were used to exemplify favored odds for support of the most likely hypothesis for a given ridge density.

Statistical analyses were performed by using SPSS 15.0 and Statistica 7 software. In all cases, the level of significance was taken as equal to or less than 0.05.

3. Results

Table 1 gives mean RD values for all 10 fingers by area and sex for both Argentinian populations (PQ and RA). In each case, a

Table 1
Descriptive statistics of ridge density (10 fingers mean) in males and females from Argentinian samples (Puna-Quebrada and Ramal).

	Males			Females		
	Radial	Ulnar	Proximal	Radial	Ulnar	Proximal
Ramal (n = 200)						
Mean	17.04	16.10	14.08	19.08	17.75	15.12
SD	1.68	1.61	1.30	1.84	1.69	1.40
Minimum	13.70	12.00	10.00	15.50	14.10	11.38
Maximum	20.80	20.10	17.60	23.48	21.71	20.50
Puna-Quebrada (n = 193)						
Mean	16.67	16.39	14.33	18.47	17.62	16.13
SD	1.78	1.75	1.31	1.56	1.62	1.54
Minimum	13.60	13.00	11.50	14.90	13.60	12.20
Maximum	22.40	21.90	18.00	22.80	21.20	20.25

SD – standard deviation.

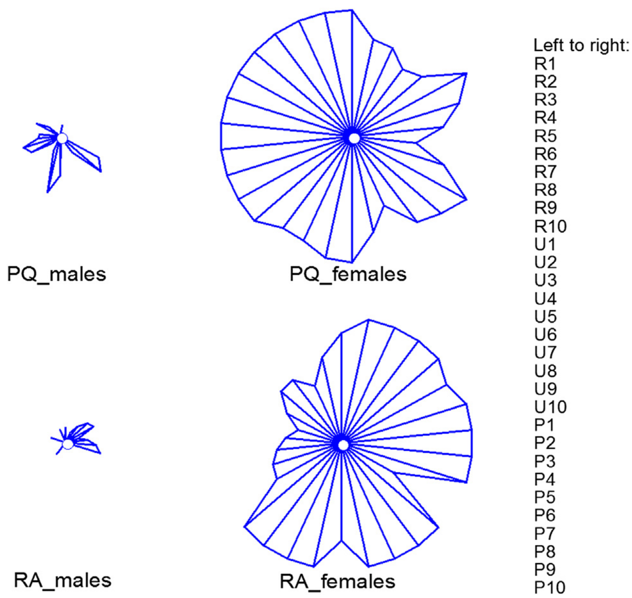

Fig. 2. Star plots according to sex and population sample: PQ (Puna-Quebrada) and RA (Ramal). Ridge count areas: R (radial), U (ulnar) and P (proximal). Fingers: $i = 1$–10.

decreasing gradient of RD according to topological area appears, so that radial means are higher than the corresponding ulnar means, and proximal means are the lowest. Moreover, the female mean are always significantly higher ($p < 0.001$) than the male mean of the same population and area. When comparing both populations by sex, no statistically significant differences were found in males in any of the three areas, whereas females significantly differed for radial ($p < 0.05$) and proximal area ($p < 0.001$).

Ridge density in all three areas correlated positively and significantly ($p < 0.001$); thus, individuals who presented a high or low ridge density in one of the areas also presented this characteristic in the other two areas.

3.1. *Finger differences in RD by topological area, sex and population sample*

Fig. 2 shows a star plot of the 30 numeric variables, where each variable is the mean for RD in each area and for each of the 10 fingers. For a given observation, the length of each ray is proportional to the size of that variable. The variables were assigned to the rays of the star in the following order: radial, ulnar and proximal areas in the 10 fingers. The variables were arranged clockwise around the perimeter, with the first item at the 12 o'clock position. Each star represents a population and sex group, and the differences among them are clearly displayed. The dominant pattern in Fig. 2 is that of females, with long rays indicating greater RD in both populations. By contrast, the stars for males are the smallest for both populations.

Mean RD for each area and finger from both samples is shown in Fig. 3. In both populations and both sexes, the radial and ulnar areas of the thumb and index fingers show lesser RD than that of other fingers (middle, ring and little), which means the presence of thicker ridges in these two fingers. However, in the proximal area, RD is greater in the thumb and ring fingers than in the index, middle and little fingers.

With regard to sex differences, females show a statistically significant ($p < 0.001$) higher RD than males for every finger, except

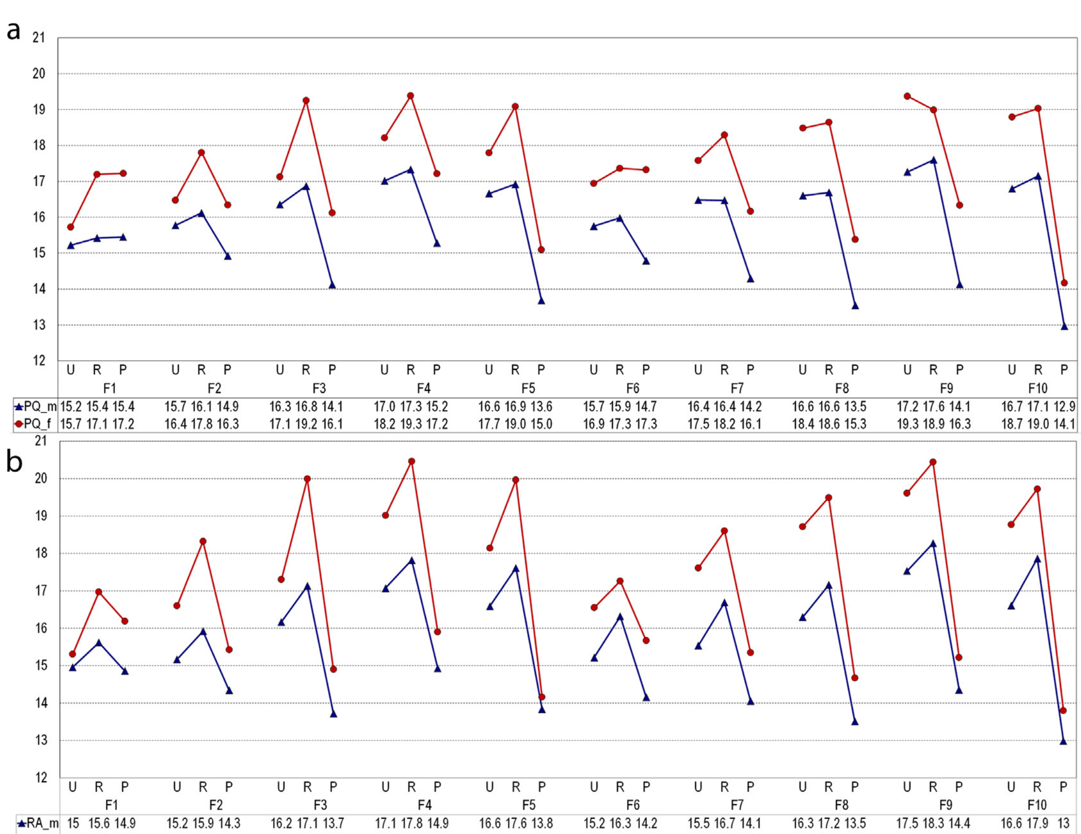

Fig. 3. Mean ridge density for each area by finger and sex (m = males, f = females). (a) PQ = Puna-Quebrada; (b) RA = Ramal. U, ridge density ulnar; R, ridge density radial; P, ridge density proximal. Fingers ($i = 1,…,10$).

for the ulnar area of the thumb (F1) in both populations and for the proximal area of the right little finger (F5) in the RA sample (Fig. 3).

When comparing RA and PQ males, no statistically significant differences in ridge density are found for any finger or area (except for ulnar area in F7), nor for the global 10 fingers mean. Nevertheless, RD in females shows a greater number of differences among areas. The proximal area is significantly higher in PQ females than in RA females for every finger ($p < 0.05$ to $p < 0.001$), except in F10, whereas differences of that statistical significance are only found in F4, F5, F8 and F9 for the radial area and in F4 for the ulnar area.

Men and women in the PQ sample (Fig. 3a) show topological differences in RD on fingerprint surface, so that higher RD is found on the radial than on the ulnar area, and the proximal area shows the lowest values in all fingers but in the right thumb (F1) in both sexes and left ring (F9) and left thumb (F6) in females. These differences reach statistical significance (Friedman test for related samples, $p < 0.001$) in all fingers but the right thumb (F1) in males and the left thumb (F6) in females. In subjects from RA (Fig. 3b), the same basic pattern for the ridge density (radial > ulnar > proximal) is found in all fingers (except for F1 in females). The differences among the three areas are statistically significant ($p < 0.001$) in each finger. When only distal area of the fingerprints is considered, all fingers show statistically significant differences (Wilcoxon–Mann–Whitney test, $p < 0.05$) for the RD between the radial and ulnar areas in the RA sample. Nevertheless, in the PQ sample, these differences are significant in females for all right-hand fingers and the index of the left hand (F7), and in males for right index (F2) and right middle (F3) fingers and left little finger (F10).

The ridge density of the radial and ulnar areas by sex and population (Puna-Quebrada and Ramal) was compared by finger; the results are shown in Table 2. In the bottom left-hand side (in darker

Table 2

Significant differences between the mean ridge density of the fingers (F) ($i = 1,\dots,10$) on the areas (radial and ulnar) are shown through the p-value. When $p < 0.05$ an asterisk symbol appears and when $p > 0.1$ a hyphen appears. PQ: Puna-Quebrada, RA: Ramal.

		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	RADIAL
F1	PQ_♂		*	*	*	*	*	*	*	*	*	
	RA_♂		0.098	*	*	*	*	*	*	*	*	
	PQ_♀		*	*	*	*	-	*	*	*	*	
	RA_♀		*	*	*	*	-	*	*	*	*	
F2	PQ_♂	*		*	*	*	-	0.099	*	*	*	
	RA_♂	-		*	*	*	-	*	*	*	*	
	PQ_♀	*		*	*	*	0.082	*	*	*	*	
	RA_♀	*		*	*	*	*	-	*	*	*	
F3	PQ_♂	*	*		*	0.084	*	0.059	-	*	0.058	
	RA_♂	*	*		*	0.064	*	*	-	*	*	
	PQ_♀	*	*		-	-	*	*	*	-	-	
	RA_♀	*	*		*	-	*	*	-	0.058	-	
F4	PQ_♂	*	*	*		*	*	*	*	0.072	-	
	RA_♂	*	*	*		-	*	*	*	0.062	-	
	PQ_♀	*	*	*		-	*	*	*	-	-	
	RA_♀	*	*	*		*	*	*	*	-	0.083	
F5	PQ_♂	*	*	0.090	-		*	0.093	-	*	0.055	
	RA_♂	*	*	*	*		*	*	0.068	*	-	
	PQ_♀	*	*	*	-		*	*	0.094	-	-	
	RA_♀	*	*	*	*		*	*	-	-	-	
F6	PQ_♂	*	-	*	*	*		*	*	*	*	
	RA_♂	-	-	*	*	*		0.097	*	*	*	
	PQ_♀	*	*	-	*	*		*	*	*	*	
	RA_♀	*	-	*	*	*		*	*	*	*	
F7	PQ_♂	*	*	-	*	-	*		-	*	*	
	RA_♂	*	-	*	*	*	-		*	*	*	
	PQ_♀	*	*	-	*	-	*		0.053	*	*	
	RA_♀	*	*	-	*	*	*		*	*	*	
F8	PQ_♂	*	*	-	*	-	*	-		*	*	
	RA_♂	*	*	-	*	-	*	*		*	*	
	PQ_♀	*	*	*	-	*	*	*		-	-	
	RA_♀	*	*	*	-	*	*	*		*	-	
F9	PQ_♂	*	*	*	-	*	*	*	*		*	
	RA_♂	*	*	*	*	*	*	*	*		0.077	
	PQ_♀	*	*	*	*	*	*	*	*		-	
	RA_♀	*	*	*	*	*	*	*	*		0.077	
F10	PQ_♂	*	*	*	-	-	*	*	-	0.094		
	RA_♂	*	*	*	0.083	-	*	*	-	*		
	PQ_♀	*	*	*	0.068	*	*	*	-	*		
	RA_♀	*	*	*	-	*	*	*	-	*		
ULNAR												

type), differences between fingers, compared two by two for the ulnar area, are shown, and the same data are given for the radial area in the top right-hand side (in lighter type). The significant differences are shown with an asterisk symbol to indicate that $p < 0.05$, but a hyphen appears when $p > 0.1$. For example, it can be seen that in PQ males, the radial area of the right thumb (F1) presents significant differences from the radial area of each other finger, whereas the radial area of the right thumb of RA males presents significant differences from the radial areas of all the other fingers except for right index (F2).

3.2. Spanish versus Argentinian comparison

The results obtained for Argentinian samples were compared with those of a Spanish population sample.[38] The frequencies found for the main types of patterns (arches, radial loops, ulnar loops and whorls) for the three population samples are shown in Fig. 4a. In all the samples the ulnar loop is the most frequent pattern, followed by the whorl, while the arch and the radial loop present considerably lower frequencies. Significant dependence is found between the general patterns and the population ($chi^2 = 78.952$ $df = 6$; $p < 0.0001$). The correspondence analysis shown in Fig. 4b explains 100% of the inertia. The first dimension, which explains 90% of the inertia, separates the Spanish sample from both Argentinian samples.

The main pattern frequency distribution for each finger was analyzed, revealing a significant association between whorls and thumbs and ring fingers, between ulnar loops and middle and little fingers, and between arches and radial loops and index fingers. The relationship between the type of pattern and RD was statistically analyzed only for whorls and ulnar loops due to the low frequency of occurrence of arches and radial loops. As in the Spanish sample,[38] both Argentinian samples show statistically significant differences ($p < 0.0001$) in RD between whorls and ulnar loops for the proximal area (RD whorls > RD ulnar loops). Moreover, in Argentinian samples these differences also appear for the ulnar area in PQ females ($p = 0.025$) and RA males ($p = 0.001$).

In order to compare the RD between Spanish and Argentinian populations, the PQ and RA samples were joined. Fig. 5 gives the mean RD obtained for each area and finger by sex from the Argentinian population we sampled, compared with those obtained from a Spanish population sample studied by Gutiérrez-Redomero et al.[38] The Argentinian sample presents a higher mean RD than the Spanish sample for each area (radial, ulnar and proximal) of each finger. A means comparison shows that RD in the Argentinian population sample is significantly higher ($p < 0.001$) for all the areas of all fingers, except in female radial area in F10, and in males for radial area in fingers F3, F4, F5, F8 and F10 and for ulnar area in finger F5.

3.3. Likelihood ratio estimates

The distribution of ridge density frequencies is shown in Fig. 6. Probabilities $P(RD|C)$ and $P(RD|C')$ were calculated from relative frequencies of ridge density and then used for inferring the most likely sex, by means of the likelihood ratios (LRs) shown in the left side of Table 3. These results show that in both Argentinian samples, 16 ridges/7.07 mm or less have an LR > 1 for radial area and 14 ridges/7.07 mm have an LR > 1 for proximal area. However, in the ulnar area the threshold would change from 15–16 in the PQ sample to 17–18 ridges/7.07 mm in the RA sample. The odds for the three areas (radial, ulnar and proximal) were obtained; as an example, the radial area for the PQ sample is shown in Table 4. Assuming equal prior probabilities for both sexes ($P(C) = P(C') = 0.5$), 16–17 ridges/7.07 mm on this area determines a threshold of sex differentiation. Presuming men are more likely to commit a crime, prior probabilities can be set at a higher value (for example $P(C) = 0.7$), so the threshold would change to 18–19 ridges/7.07 mm.

For inferring population origin, only the male sample was considered. The right side of Table 3 shows the probabilities P(RD|C) and P(RD|C′) that were estimated from relative frequencies of male ridge density and then used to infer the most likely population origin (Argentinian or Spanish) by means of the LRs. The results show that 17 ridges/7.07 mm or less have an LR > 1 for radial area, which means that the LR supports a Spanish origin; nevertheless, 18 ridges/7.07 mm or more have an LR < 1, meaning that the LR supports an origin from the Argentinian population. In the ulnar area, this threshold is 15–16 ridges/7.07 mm and in the proximal area 12–13 ridges/7.07 mm.

The results show that depending on the prior probabilities of Argentinian men and Spanish men, the odds change. Table 5 shows the probability densities and LRs derived from observed ridges in the proximal area. Our results show that given the same prior probability for both populations, P(C) = P(C′) = 0.5, if a fingerprint presents a ridge count of 12 ridges/7.07 mm or less, it was most likely made by a Spanish male. However, if the ridge count for the same area is 13 ridges/7.07 mm or more, the fingerprint was most likely made by an Argentinian male.

4. Discussion

Unlike the traditional method for counting ridges, the approach used in this study allows an assessment of topological differences in ridge density on the same finger, and of topological differences in

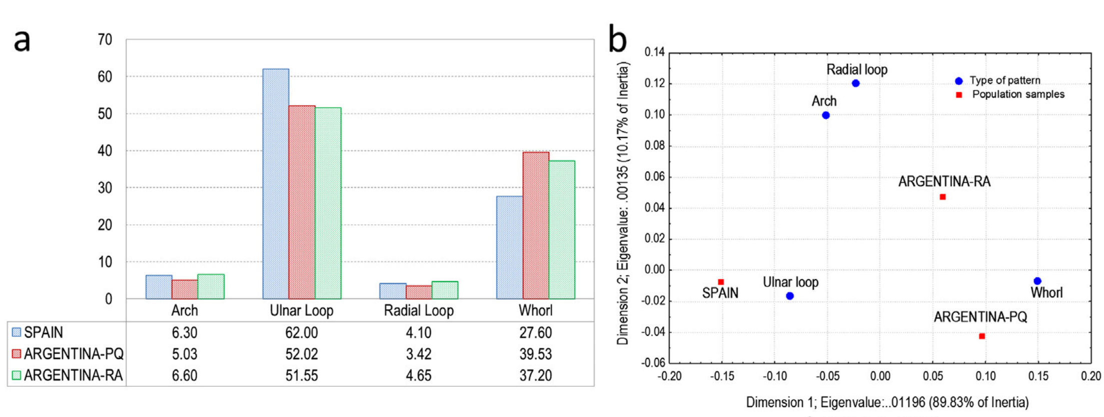

Fig. 4. (a) Relative frequencies for the type of patterns. (b) Analysis of correspondence between general patterns and the population samples.

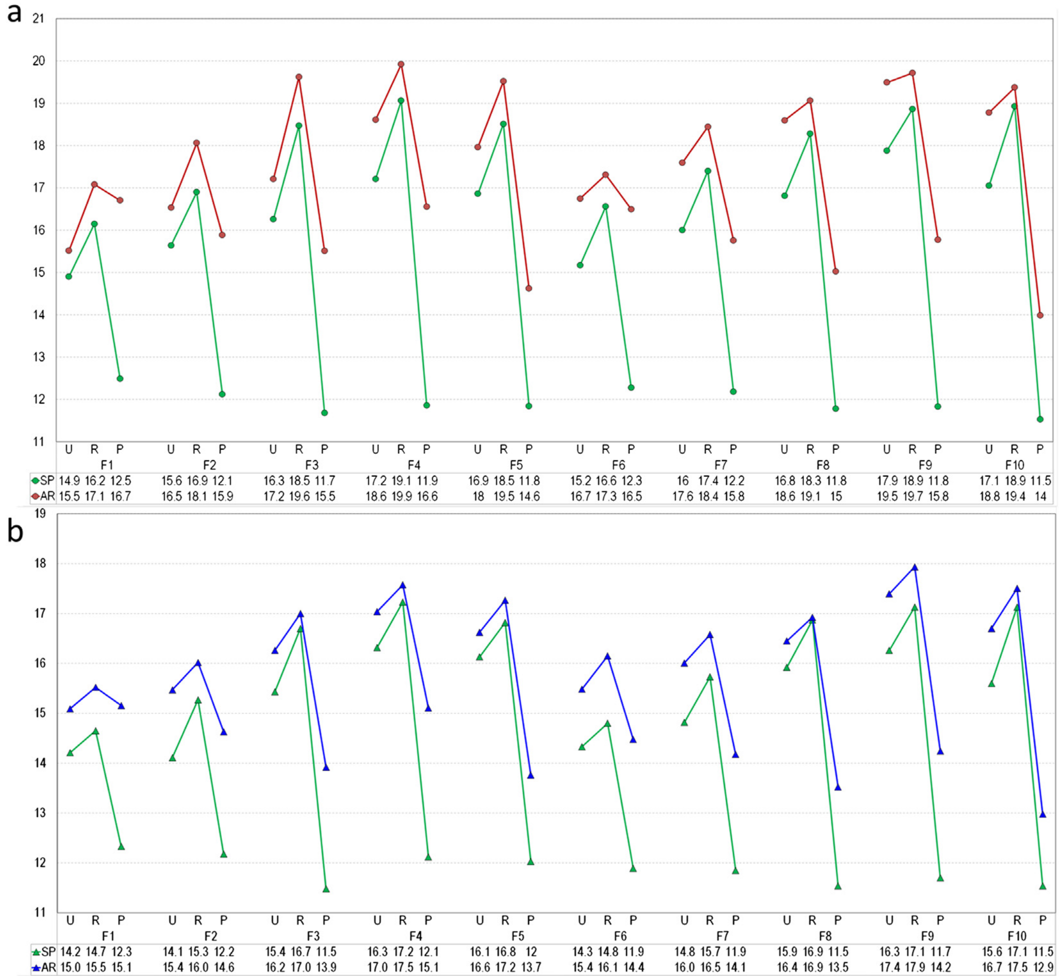

Fig. 5. Mean ridge density for each area and finger by sex. (a) Female means, (b) male means. U, ulnar area; R, radial area; P, proximal area; SP, Spain; AR, Argentina (Puna-Quebrada and Ramal samples).

patterns without a triradius or delta, such as arches. This type of pattern should not be underestimated systematically in studies, especially when low frequency affects the weight of evidence.[36]

The variability observed in RD in the three areas analyzed reflects differences in ridge breadth on the fingerprint surfaces of the samples studied. These differences show, in general, a distribution pattern of higher density, and thus narrower ridges, in the radial and ulnar areas of the distal region. In contrast, a lower RD was observed in the proximal region, reflecting the presence of thicker ridges in this fingerprint region. These results agree with those found in the adult Mataco-Mataguayo population,[8] the only South American population analyzed (apart from this study) with the same methodology, and with findings for the Spanish population.[38] This distoproximal gradient observed in the fingerprints corresponds with that indicated by Cummins et al.[24] and Ohler and Cummins,[25] who detected a distoproximal gradient extending from the fingertips (narrower ridges) to the proximal region of the palm (thicker ridges).

In the present study, the female fingerprints show significantly finer ridges (higher mean counts) than the male ones in all the valuated areas (radial, ulnar and proximal). Unlike the Spanish population,[38] where no significant differences between sexes were found in the proximal area, the females from our sample show significantly higher RD than males in this area. These results have also been found in Mataco-Mataguayo adults.[8]

Sexual differences in ridge breadth have been reported in bibliography,[8,37–43] in such a way that males show wider ridges than females. Several factors have been proposed to contribute to these sex differences. One of these factors would be the sexual dimorphism in body size and proportions, so that a given ridge width accommodated in a larger surface would result in a lower RD in males.[50] Another proposed cause of sex differences would be related with sex chromosomes, so it has been shown a tendency to increase the ridge breadth with the number of sex chromosomes in the karyotype, with the narrowest being found in subjects with Turner's syndrome (X) and the widest for XYY males.[7,27,50] Since ridges are not formed simultaneously over the entire hand, differential growth would be a possible factor in the regulation of ridge breadth.[2,3,51,52] Finally, it has also been suggested that the degree of ridge breadth might be related to hand use; if a more intense use of hands in men is assumed, it could be expected an increase of muscular development, which in turn could produce skin broadening of the ridges and a decrease of male RD.[25,50]

Within each analyzed sample (PQ and RA), the difference between males and females is higher in the radial area (RA: 2.04 ridges; PQ: 1.67 ridges) than in the ulnar one (RA: 1.65 ridges; PQ: 1.23 ridges). On the other hand, the comparison of female fingerprints between PQ and RA samples shows significant differences for two areas, radial and proximal areas, while males do not present significant differences in any of the three studied areas.

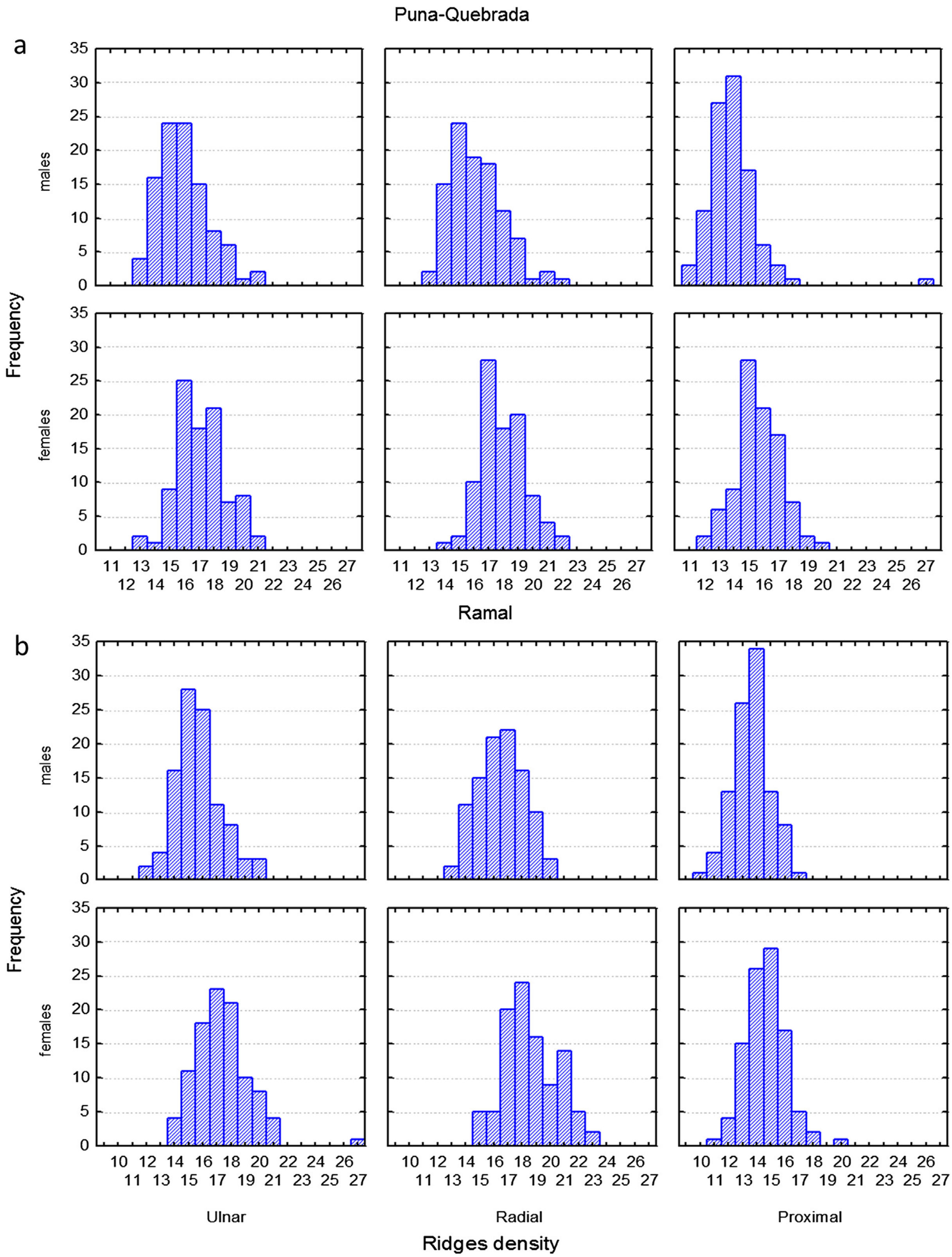

Fig. 6. Absolute frequency distribution of dermal ridge density. (a) Puna-Quebrada, $n = 193$, (b) Ramal, $n = 200$.

Regarding the pattern of distribution of RD by finger, both sexes show the same general pattern, although the female fingerprints in each finger show significantly finer ridges (higher mean counts) than in the corresponding digits in men. Thus, the increasing order of RD for radial and ulnar areas is thumb < index < middle < little < ring fingers. Accordingly, topological distribution indicated that the thumbs have a greater ridge breadth than all the other fingers, while the narrowest ridges appear in the ring fingers. These results agree

Table 3
Likelihood ratios for ridge count area by sex and population origin. Left side, LR C (male)/LR C′ (female) ridge count by area and population sample. PQ, Puna-Quebrada; RA, Ramal. Right side, LR C (Spanish)/LR C′(Argentinian) ridge count area. LR > 1 is shown in bold.

Ridge density	LR C (male)/LR C′ (female)						LR C (Spanish)/LR C′ (Argentinian)		
	Radial		Ulnar		Proximal		Radial	Ulnar	Proximal
	PQ	RA	PQ	RA	PQ	RA			
≤10									**48.00**
11									**8.57**
12					**6.51**	**3.60**			**2.25**
13					**4.19**	**1.73**		**2.40**	0.45
14	**15.81**	**5.50**			**3.20**	**1.31**	**1.20**	**1.69**	0.15
15	**11.16**	**2.55**	**3.41**	**3.00**	0.56	0.45	**1.28**	**1.23**	0.08
16	**1.77**	**1.39**	0.89	**4.20**	0.27	0.47	**1.05**	0.86	
17	0.60	0.48	0.78	**1.10**	0.17	0.20	**1.30**	0.31	
18	0.57	0.38	0.35	0.67			0.52	0.38	
19	0.33	0.30	0.80	0.63			0.25	0.04	
≥20	0.27	0.23	0.28	0.10					

with those obtained for Mataco-Mataguayo[8] and Spanish populations[38] and coincide with the topological distribution of ridge breadth found by Cummins et al.[24] and Ohler and Cummins.[25] However, the general ranking for the proximal area shows a different arrangement with an increasing ridge count as follows: little < middle < index < ring = thumb. Therefore, the little and middle fingers present the thickest ridges and the thumbs and ring fingers the finest ridges in this area. A similar arrangement has been found in the Mataco-Mataguayo population,[8] unlike the Spanish population, where the proximal RD increases as follows: middle < little < ring < index < thumb.[38]

The comparison with the Spanish population[38] of RD by area, finger and sex shows a similar distribution pattern. Nevertheless, the differences observed between the distal and proximal regions in the Argentinian sample are smaller, both in males and females, revealing greater homogeneity in ridge thickness on the fingerprint surface of these South American populations, especially in thumbs.

With respect to main pattern type (arches, radial loops, ulnar loops and whorls), the South American Indians have greater variation in frequency than any other American population (Eskimos, North American Indians and Central American Indians).[53,54] The frequencies of finger pattern type found in the two Argentinian samples agree with those described for South American populations.[55,56] Although the Argentinian samples were characterized by presenting more whorls and fewer ulnar loops than the Spanish population sample, in both populations the whorls presented significantly finer ridges than ulnar loops in proximal area.

Table 6 shows the mean RD results found in other populations for the radial area, which for the most part has been the only area analyzed by studies. In all populations, females present a significantly higher RD than males, which could suggest a universal pattern of sexual dimorphism in this trait. Moreover, the results show a remarkable interpopulational variability in RD. Thereby, in this area, the Argentinians show a higher RD, and thus finer ridges, than the Spanish population, and in turn all of them present a higher RD than sub-Saharans. The rest of the populations present a lower RD. These differences could be accounted for by intrinsic characteristics of the populations studied, but a portion of these may be determined, to some extent, by methodological variations in the selection of the count area and the method used to obtain fingerprints (rolled or plain prints). In order to avoid these methodological differences, we have standardized the location of the count areas, allowing us to assert that the significant differences found among Spanish, Argentinian and sub-Saharan populations are due only to population differences.

Table 4
Data of probability densities and likelihood ratios derived from observed ridge in radial area for Puna-Quebrada sample. C, male; C′, female.

Ridge density (RD)	Probability distributions		Likelihood ratio P(RD|C)/P(RD|C′)	Odds	
	Males P(RD|C)	Females P(RD|C′)		P(C) = 0.5, P(C′) = 0.5	P(C) = 0.7, P(C′) = 0.3
≤14	0.17	0.01	15.81	Male (0.94) > female (0.06)	Male (0.97) > female (0.03)
15	0.24	0.02	11.16	Male (0.92) > female (0.08)	Male (0.96) > female (0.04)
16	0.19	0.11	1.77	Male (0.64) > female (0.36)	Male (0.80) > female (0.20)
17	0.18	0.30	0.60	Male (0.37) < female (0.63)	Male (0.58) > female (0.42)
18	0.11	0.19	0.57	Male (0.36) < female (0.64)	Male (0.57) > female (0.43)
19	0.07	0.22	0.33	Male (0.25) < female (0.75)	Male (0.43) < female (0.57)
≥20	0.04	0.15	0.27	Male (0.21) < female (0.79)	Male (0.38) < female (0.62)

Table 5
Data of probability densities and likelihood ratios derived from observed ridge in proximal area of males. C, Spanish; C′, Argentinian.

Ridge density (RD)	Probability distributions		Likelihood ratio P(RD|C)/P (RD|C′)	Odds	
	Spanish P(RD|C)	Argentinian P(RD|C′)		P(C) = 0.5, P(C′) = 0.5	P(C) = 0.7, P(C′) = 0.3
≤10	0.24	0.01	48.00	SP (0.98) > AR (0.02)	SP (0.99) > AR (0.01)
11	0.30	0.04	8.57	SP (0.90) > AR (0.10)	SP (0.95) > AR (0.05)
12	0.27	0.12	2.25	SP (0.69) > AR (0.31)	SP (0.84) > AR (0.16)
13	0.12	0.27	0.40	SP (0.31) < AR (0.69)	SP (0.51) > AR (0.49)
14	0.05	0.33	0.10	SP (0.13) < AR (0.87)	SP (0.26) < AR (0.74)
≥15	0.02	0.25	0.08	SP (0.07) < AR (0.93)	SP (0.16) < AR (0.84)

Table 6
Mean of ridge density according to the method described by Acree[37] at radial region in different studies.

Sample	Reference	Ridge density mean (SD)	
		Males	Females
Afro-American (USA)	Acree[37]	10.90 (1.15)	12.61 (1.43)
Caucasian-American (USA)	Acree,[37]	11.14 (1.31)	13.32 (1.24)
Southern India (Karnataka)	Nayak et al.[41]	11.05 (1.11)	14.20 (0.63)
Southern India (Karnataka)	Gungadin[40]	12.80 (0.90)	14.60 (0.085)
Southern India (Karnataka)	Nithin et al.[42]	12.57 (1.49)	14.15 (1.68)
Malaysia	Nayak et al.[43]	11.44 (0.988)	13.63 (0.906)
China	Nayak et al.[43]	11.73 (1.066)	14.15 (1.038)
sub-Saharan	Gutiérrez-Redomero et al.[44]	14.33 (1.22)	–
Spain	Gutiérrez-Redomero et al.[38]	16.23 (1.39)	17.91 (1.47)
Argentina (Mataco-Mataguayo)	Gutiérrez-Redomero et al.[8]	16.62 (2.71)	17.82 (2.87)
Argentina (Puna-Quebrada)	Present study	16.67 (1.78)	18.47 (1.56)
Argentina (Ramal)	Present study	17.04 (1.68)	19.08 (1.84)

We therefore consider it to be important to clearly define the position of the ridge count area in order to carry out comparative studies of any kind. This standardization is particularly relevant in view of the forensic applications of this feature for inferring the sex or ethnicity of an individual from fingerprints of an unknown origin. Consequently, more research is needed to assess the extent and causes of population differences, which would allow its use in a forensic context to discriminate between populations.

In this study, Bayes' theorem has been used to establish the discrimination threshold between both sexes (within the Argentinian population) and between populations (between Argentinian and Spanish populations), assuming that the prior probabilities for each sex and for each population are known.

The RD probabilities were used for inferring the most likely sex, by means of the likelihood ratios (LRs) for three areas (radial, ulnar and proximal). For instance, a fingerprint from PQ showing up to 16 ridges/7.07 mm on the radial area has a high probability of being from a male, whereas a ridge count of 17 ridges/7.07 mm or more has a high probability of being from a female. Hence, a fingerprint showing 15 ridges/7.07 mm, in this area, has a high probability of originating from a male (0.92) versus female (0.08).

Likewise, the RD probabilities were used for inferring the most likely origin by means of the likelihood ratios (LRs) for three areas (radial, ulnar and proximal). Thus, taking an equal prior probability for both populations (50% Spanish and 50% Argentinian), an analysis of the LR obtained for the proximal area indicated that the discrimination threshold was a ridge count of 12 ridges/7.07 mm. Thus, a fingerprint showing 11 ridges/7.07 mm, in this area, has a high probability of being Spanish (0.90) versus Argentinian (0.10).

The results obtained in this study provide additional information to assess the weight of the evidence in terms of likelihood ratio, contributing to improve personal identification from fingerprint impressions. The application of degrees of probability in inferring sex or population could facilitate the laborious process of seeking and identifying subjects, and so helping the fingerprint expert (criminal investigator) to direct the search toward the most probable group of suspects. In addition, this technique could prove useful in analyzing impressions that until now have not been recovered or considered for examination because of their low quality, but for which it is possible to count the ridges.

5. Conclusions

This study shows the existence of topological differences in ridge thickness on finger surface, with narrower ridges in the distal region and thicker in the proximal. In addition, finger differences in the distal region have been highlighted in such a way that fingers from the radial side of the hand (thumb and index) have thicker ridges than fingers from the ulnar side (ring and little).

Despite the altitudinal gradient, both Argentinian samples (PQ and RA) present a similar topological and digital RD distribution and are consistently different from the Spanish sample.

On the other hand, females have narrower ridges than males in all areas and all fingers. These findings can be applied in the field of forensic science in order to improve sex identification using fingerprints.

Finally, it is relevant to point out that the differences observed between the Argentinian and Spanish samples studied in the three areas of the fingers, especially in proximal area, could facilitate discrimination between the populations based on the ridge density observed in a fingerprint impression.

Ethical approval

Not required.

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Conflicts of interest

None.

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